International Journal of Innovation and Applied Studies
ISSN 2028-9324 Vol. 40 No. 2 Aug. 2023, pp. 520-531

http://www.ijias.issr-journals.org/

Contribution of LandSat OLI imagery and field indices to the structural cartography of the aquifer system of black Volta catchment in Côte d'Ivoire

Armel Kouadio KOUAME[1], Marc YOUAN TA[1-2], Bertrand Houngnigbo AKOKPONHOUE[3], and Omer Zéphir De LASME[4]

[1]Laboratory of soil, water and geomaterials sciences, Faculty of Earth Sciences and Mining Resources, University Felix Houphouët Boigny of Cocody, 22 BP 582 Abidjan 22, Côte d'Ivoire

[2]Research and Application Center for Remote Sensing (CURAT), Faculty of Earth Sciences and Mining Resources, University Felix Houphouët Boigny of Cocody 22 BP 801 Abidjan 22, Côte d'Ivoire

[3]Laboratoire d'Hydrologie Appliquée, Institut National de l'Eau (INE), Université d'Abomey-Calavi, 01 BP. 526 Cotonou, Benin

[4]Department of Geosciences, Training and Research Unit, University Péléforo Gon Coulibaly, Korhogo, Côte d'Ivoire

ABSTRACT: Fracture aquifers are actual major issue in hydrogeology. They are an essential resource for many populations around the world. The present study focuses on major fractures that control groundwater and surface water flow, and play a key role in the productivity of fractured reservoirs. The use of numerical processing techniques (Selective Principal Component Analysis (SPCA), band ratios) and directional filtering by Sobel and Yésou allowed the identification of major fractures in the Black Volta Basin in Côte d'Ivoire. Validation of the latter was done by several field works (geology, hydrogeology and geomorphology) and a comparative analysis. Three groups of NS, NE-SW and E-W lineament directions were identified from these images. The structural field data generally indicate similar directions. Field data and satellite image processing show that most of these lineaments correspond to either shear faults or veins related to Eburnian and post-Eburnian orogenic events. The comparative analysis carried out revealed concordances with previous studies and automatically detected structures in the same area. The final lineament map generated for the study area will help to identify potential areas for drilling for water supply purposes.

KEYWORDS: Remote sensing, discontinuous aquifers, major fractures, hydrogeology, Black Volta, Côte d'Ivoire.

1 INTRODUCTION

The crystalline and crystallophyllous basement regions are known for their structural complexity. The associated water resources reflect this complexity to a large extent: heterogeneous, difficult to characterize and a priori not predictive [1], 1992; [2]. These reserves are located in deep geological units called fissure aquifers which may however present more interesting hydrodynamic properties than the superficial compartments classically targeted by modern wells and boreholes which are vulnerable to anthropic contamination from the surface. These reservoirs can provide significant flow rates. The mapping of fractures is essential for the supply of drinking water in several regions of the world in general and for many countries in sub- Saharan Africa in particular where these aquifers are the only water resource. This is the case of the Black Volta Basin in Côte d'Ivoire, the subject of this study, whose terrain is occupied mainly by crystalline and crystallophyllous rocks. Such an environment already raises significant concerns about the availability of water resources given its complexity. In addition, during the low water period (decrease in rainfall and high humidity), streams, wells and boreholes dry up. In such a context, the identification of the major fractures is necessary to ensure the sustainability of the inter-seasonal availability of the groundwater resource. This requires an approach that is firstly regional and then local. The method most commonly favored by basement hydrogeologists is lineament analysis [3], [4]. A lineament is defined as any topographic alignment visible on the landscape reflecting a geologic discontinuity. Lineaments can be identified regionally by visual analysis of the landscape on topographic maps, aerial photographs (photogrammetry), and satellite images using remote sensing methods and techniques [5], [3. They can also be identified by gravity and aeromagnetic geophysical methods [6], [7]. They are subsequently verified locally from geomorphic, geological and geophysical evidence.

A mapping approach following such a process is appropriate for the structural identification of fractured environments and will therefore allow a better knowledge of them for an efficient water management.

2 GEOLOGICAL AND HYDROGEOLOGICAL FRAMEWORK

The study area (Figure 1) is the interface of the Black Volta transboundary basin in Côte d'Ivoire. It is located between latitudes 7°78 and 9°94N and longitudes 2°49 and 3°35W and delimits a vast geographical area, located in the northeast of Côte d'Ivoire. Its main river, the Black Volta (Mouhoun) River, originates in the Kong Mountains in the Dindéresso Forest Reserve, southwest of Burkina Faso. It is approximately 1,363 km long, and drains a total area of 12,836 km^2 in Côte d'Ivoire. The relief is not very rugged. The highest peak, the Bondoukou Massif, reaches an altitude of 725 m. Geologically, the basin is located in the eastern compartment of the Precambrian basement called Baoulé-Mossi (Figure 1) of Paleo-Proterozoic age and structured by the Eburnian megacycle (2400-1600 Ma). The eastern zone is covered by a complex set of geological formations classified according to age and unevenly distributed in two domains: the Quaternary domain (Holocene) and the Birimian domain (Figure 1).

From a hydrogeological point of view, the conceptual model accepted in the basement zone [8] is the presence of a superficial film (alterites), capacitive, fed by the surface, followed by a fissured horizon (intermediate decompressed zone), with very high permeability forming the second aquifer level [9]. The third aquifer level is located in the sound bedrock affected by tectonic fractures (faults). Levels 2 and 3 constitute the semi-captive part of this multilayered aquifer hosting a single water table [10].

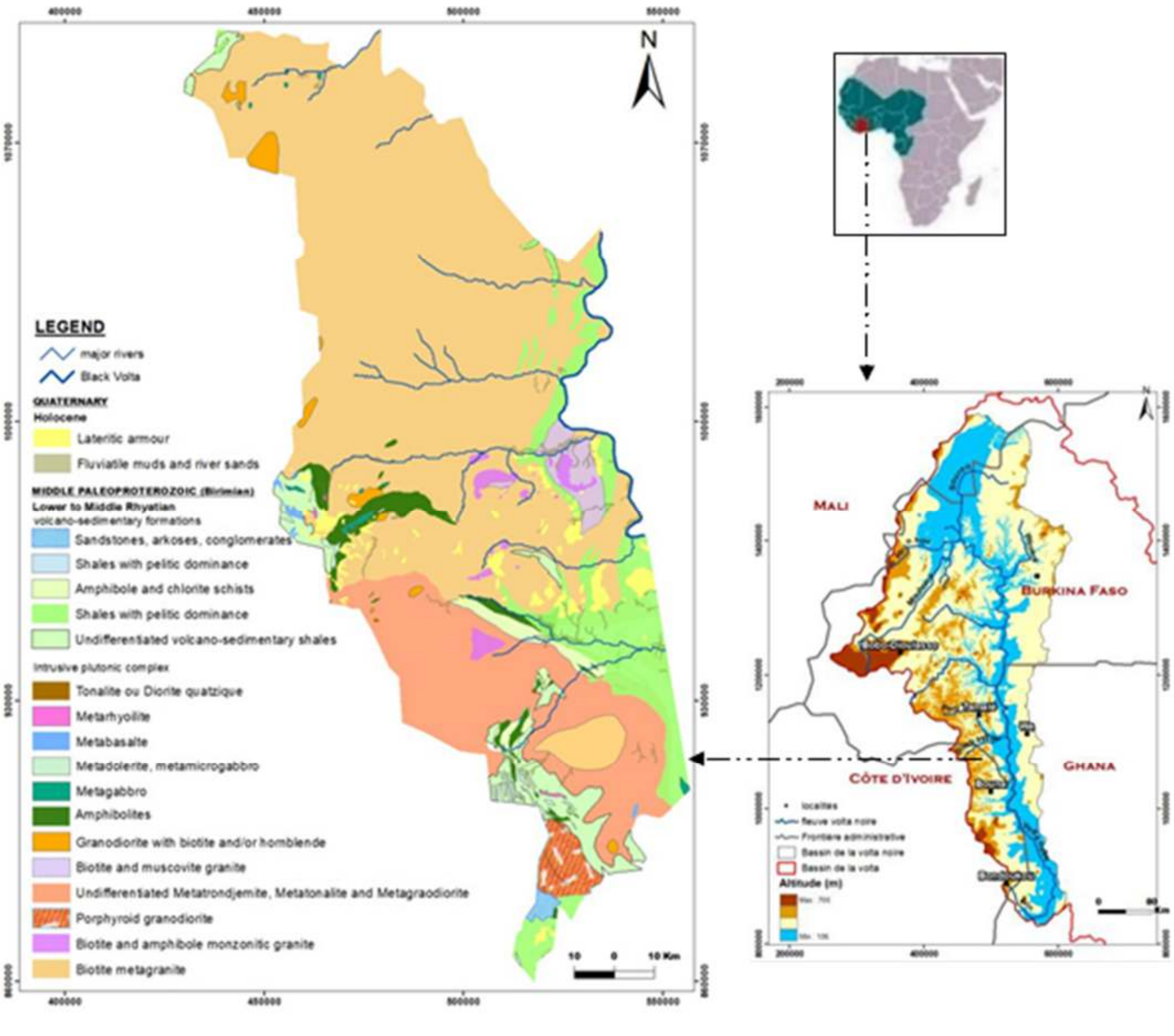


Fig. 1. Geological map of the studied area

3 MATERIALS AND METHODS

3.1 STUDY MATERIALS

A material composed essentially of satellite data, cartographic data and small field equipment was necessary to obtain the different results. The satellite data concern four (4) scenes from the LandSat OLI sensor downloaded free of charge from the United States Geological Survey (USGS) website http://earthexplorer.usgs.gov/, path and row (195-054; 196-054; 196-053; 195-055).

The cartographic data used in this study come from the archives of the "Direction de la Cartograp hie et de la Prospection Géologique (DCPG)" of the Ministry of Mines, Petroleum and Energy of Côte d'Ivoire. These are geological and topographical maps at 1: 200,000 scale of the square degrees of Tehini-Bouna; Bondoukou; Nassian; Agnibilékro/Kouamé-Dari. A GPS and a compass were also used to take the coordinates and directions of the field indices.

3.2 METHODS FOR DIGITAL PROCESSING OF SATELLITE IMAGES

Different techniques were applied to the raw satellite images before processing in order to facilitate their interpretation. A mosaic was made from four scenes of the LandSat OLI sensor. The radiometric and atmospheric correction was performed to increase the quality of the data by correcting some variations in the distribution of these caused by atmospheric and radiometric noise. Also, a harmonization of histograms by the method of equalization of histograms has helped to improve the apparent contrast on the mosaic of scenes. Most of these operations were performed on a database comprising seven bands select ed among the nine bands captured by OLI (OLI2, OLI3, OLI4, OLI5, OLI6, OLI7 and OLI8 resampled at 30 m resolution).

The methods used for digital processing in this study are: selective principal component analysis (SPCA), band ratios and moving window filtering techniques. SPCA was used to generate new component images that are in linear combination with the original images. This method enhanced the quality of the multispectral images by eliminating the redundancy of data contained in the different channels. Other structural information contained in the image could be enhanced through band ratios that aim either to reduce the sum of information or to highlight particular themes in the images. The band ratios performed are: OLI5/OLI7 ratios (attenuation of shading effects); OLI4 - OLI3 / OLI4 + OLI3 (the IC clarity index, for highlighting bare soil); OLI5 - OLI4/ OLI5 + OLI4 (NDVI vegetation index); OLI7-OLI8 /OLI7 + OLI8, (enhancement of regional lineaments); OLI7 / OLI5 (enhancement of lineaments attached to the hydrographic network). The moving window filtering technique was applied to the generated neo - channels to enhance image discontinuities using gradient [11] and directional Sobel 7×7 filters computed by assigning higher weights to the convolution matrix. The matrices are presented elsewhere [12].

3.2.1 EXTRACTION OF LINEAMENTS

The extraction of lineaments was done following a double approach: manual and automatic. First, it was done manually by visual analysis of the enhanced and/or filtered images and resulted in the location of the lineaments on the same geo-referenced data layer for each of the images (Figure 2). In order to account for the reliability and objectivity of this manual approach, the lineaments are automatically extracted for a comparative analysis. This was done using the panchromatic OLI8 image because it contains the bulk of the information to detect the maximum number of lineaments [13]. According to [14], the OLI8 band is more efficient for extracting some geo-structural features given its 15*15 meter resolution. The extraction process was performed using LINE (LINéaments Extraction) of PCI Geomatica 9.1 software. The parameters used for the automatic extraction of lineaments were determined after several simulations based on the values proposed in the literature (Table 1).

It should be noted that a control phase of the lineaments was carried out during and after the extraction. It consisted, as far as the manual extraction is concerned, in displaying on the monitor the artificial or anthropic linear structures (railroads, roads, tracks, telephone lines, boundaries of plantations, parks, etc.) previously vectored to avoid them and to eliminate these structures on the map obtained by automatic extraction after a simple overlay in a geographic information system of work with spatial reference.

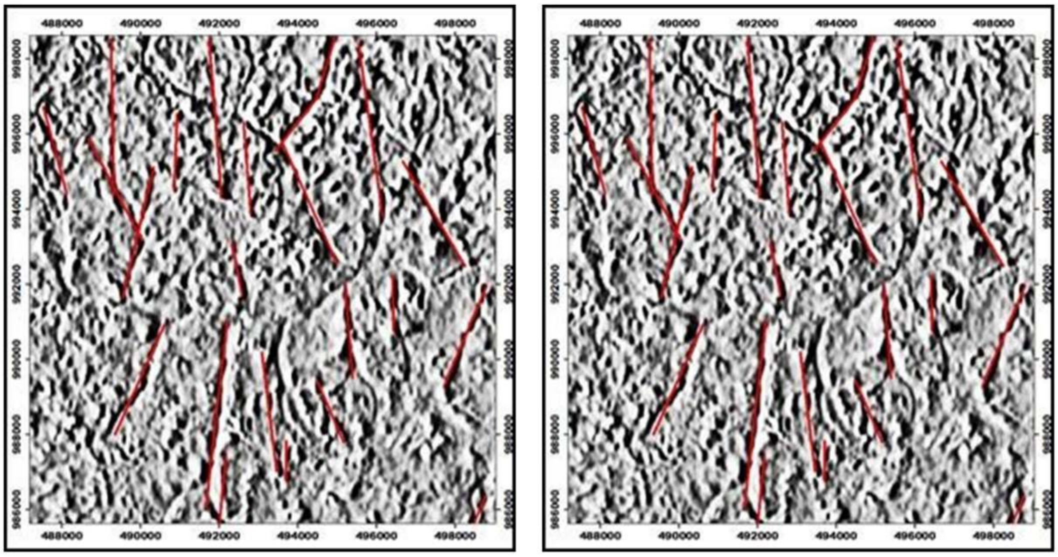


Fig. 2. Identification of lineaments on filtered images (a) filter of Sobel E-O (b); filter of Yésou.

Table 1. Parameters' values of LINE's module of PCI Geomatica

	RADI (pixel)	GTHR (pixel)	LTHR (pixel)	FTHR (pixel)	ATHR (angle)	DTHR (pixel)
LINE- PCI (par défaut)	10	100	30	03	30	20
Bishta et al. (2010)	50	30	100	03	30	70
Hubbard et al. (2012)	24	94	50	07	40	30
Abdulah et al. (2013)	12	80	30	10	30	15
Kocal et al. (2007)	12	25-60	20-30	10	20	1
Adon et al. (2014)	20	90	50	10	15	100
Golmehr (2012)	11	25	90	1	15	200
Used Parameters	24	40	50	05	20	120

3.2.2 FIELD INDICES AND LINEAMENT VALIDATION

The validation phase of the extracted lineaments is essential to judge the relevance of the method used [15], [16]. Indeed, satellite image processing regularly faces the problem of the reliability of the results they propose and their validation [1 6], [17], [18], [19], [20], [21]. This supports the obligation to proceed with the control and validation of all results from lineament mapping via the field reality. This approach consists of superimposing image data on observations collected in the field of several indices such as: lineament-vegetation alignment; lineament-wetland; lineaments-alignment of termite mounds; watercourses and observations of fractures on outcrops. The direction, position and in some cases the length and opening of fractures are measured.

Several lineaments of regional extension and particular structures discriminated on satellite images were verified and validated during a field mission. Two (02) statistical tests of validation were carried out in order to verify that the lineaments extracted from the satellite images have a structural reality and an appreciable statistical representation.

For the first validation test, the structures identified from the OLI images were frequency analyzed and the main directions were compared to field measurements and other references such as: (i) results of previous work in the study area, (ii) main directions of the hydrographic network, and (iii) orientations of lineaments from the automatic extraction approach which adds to the validation of the manually established reference map.

In the second test, the positioning of the identified structures in relation to the visited and active boreholes in the area was verified to confirm the correspondence of some identified lineaments to hydraulically active fractures exploited for water supply in the area.

4 RESULTS AND INTERPRETATION

4.1 STRUCTURAL MAPPING

The different techniques of pre-processing and digital processing of satellite images (moving window filtering) have improved the contrast on the images and thus contributed to enhance many image discontinuities. Figures 3 and 4 show the lineaments mapped from the manual and automatic extraction methods. Tables 2 and 3 highlight the basic statistical parameters of the lineament lengths. Analysis of these tables indicates that the automatic extraction provided approximately 20 times more lineaments than the manual extraction method. However, we note a substantially close average across the two lineament supports. The distribution around the mean (standard deviation) two charts is in the same order of magnitude. The lineaments identified on the 2 supports present very high coefficients of variation of the order of 200% highlighting not only the heterogeneity of the environment studied but also the similarity of the lengths despite the difference in size.

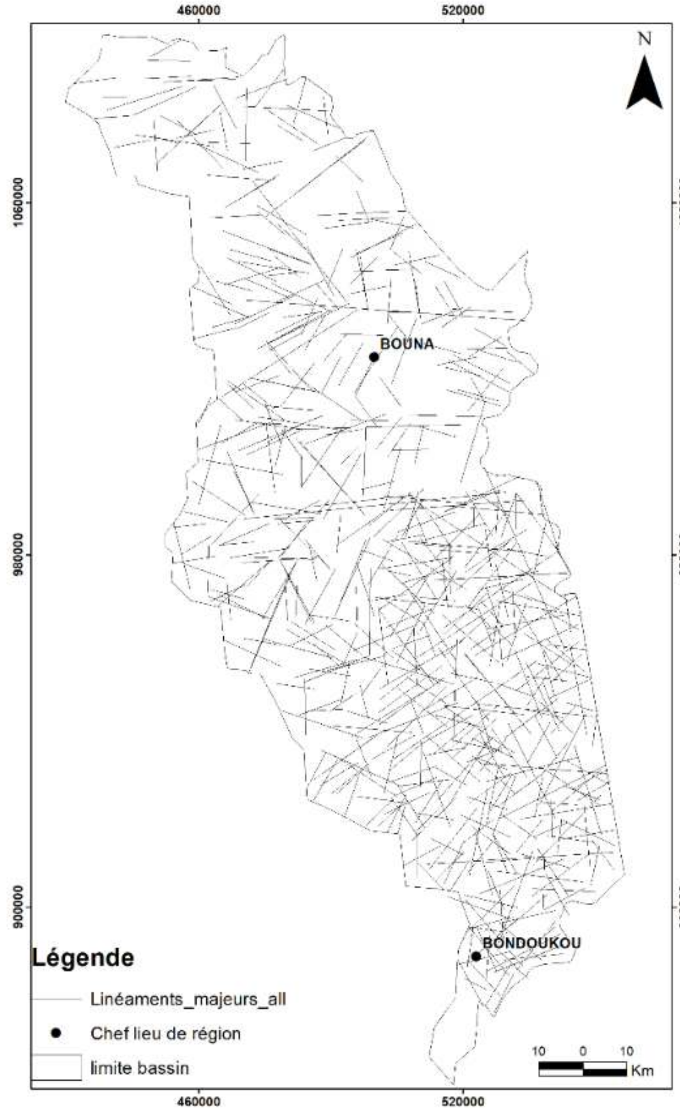


Table 2 : Statistical parameters

Effectif	1087
Minimum (m)	5486.74
Maximum (m)	64169.09
Mean (m)	13226.84
Ecart type (m)	6207.97
Mediane (m)	11243.57
Mode (m)	16345.13
Variance (m)	232023163116.92
CV (%)	213.06

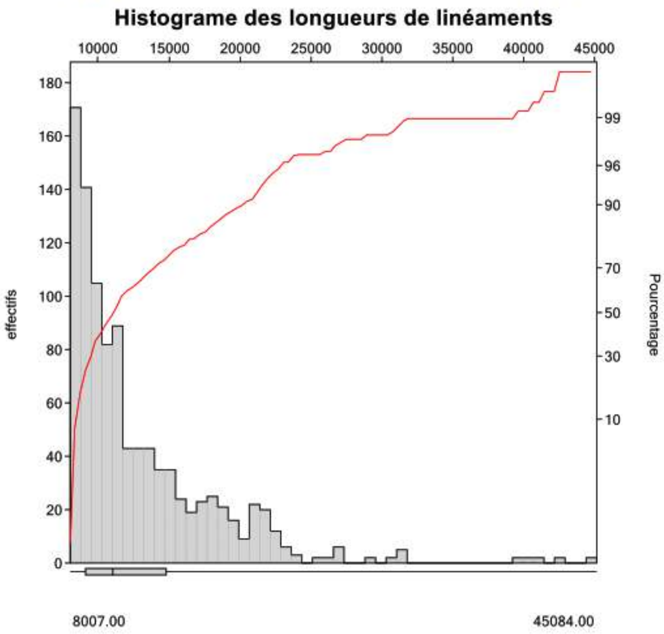


Fig. 3. Manually extracted lineament map and basic statistical parameters

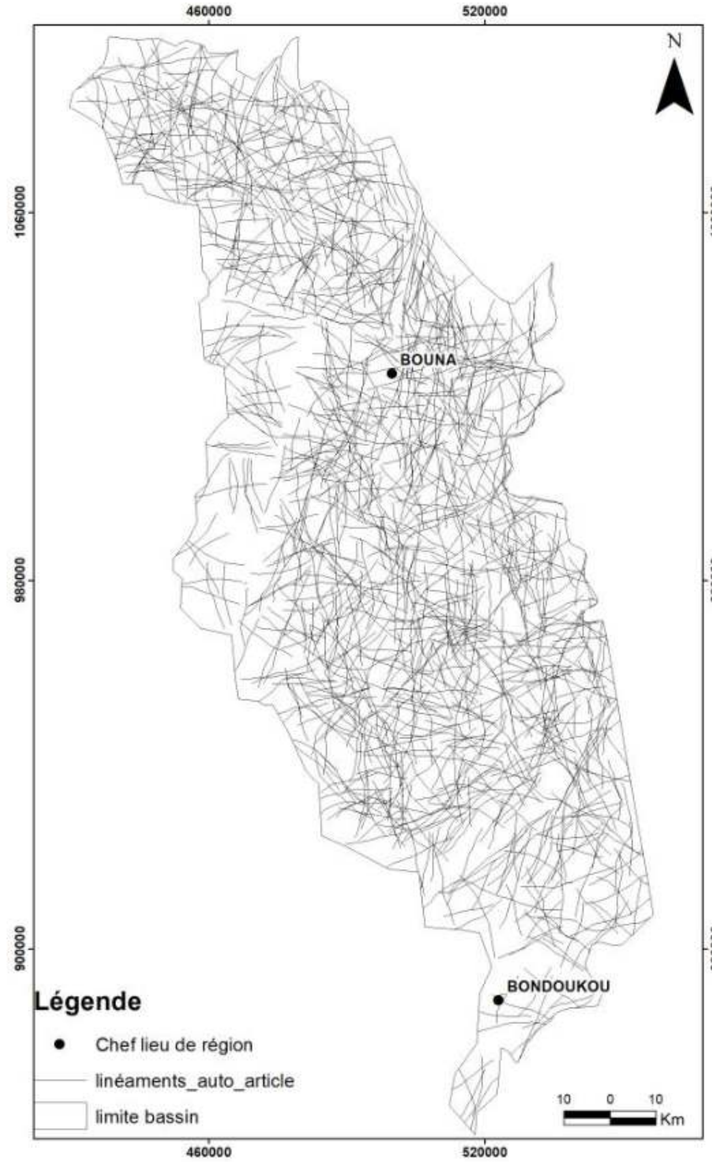


Table 3 : Statistical parameters

Effectif	23471
Minimun (m)	11038
Maximum (m)	47198
Mean (m)	16643.9
Ecart type	5634.59
Mediane (m)	14953
Mode (m)	47198
Variance (m)	31748608.6
CV(%)	295.39

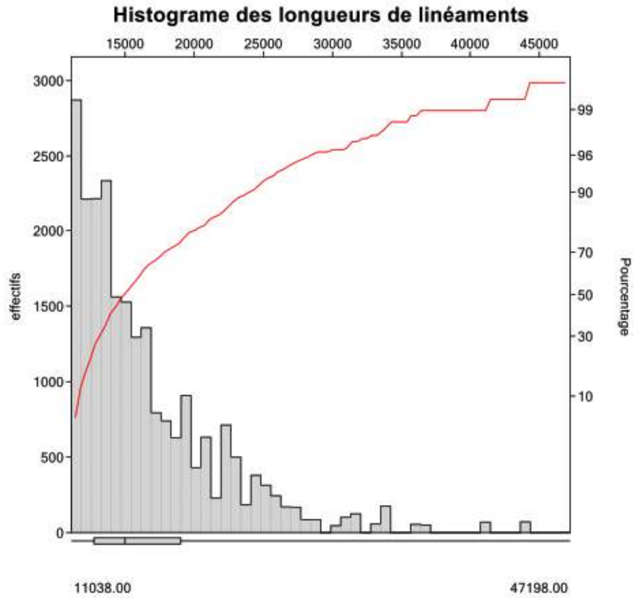


Fig. 4. Automatically extracted lineament map and basic statistical parameters

4.2 Validation Of Lineaments

4.2.1 Field truth

The lineaments of regional extension and the particular structures discriminated on the OLI satellite images were verified and validated during a field mission (figure 5). Several types of lineaments were identified: Type A lineaments (plant aliases) represent more than 52% of the lineaments identified in the study area. One distinguishes, endemic plant species namely: Panicum pharagmi-toides, Adansonia digitata, Isoberlina doka, Uapaca somon, Vitellaria paradoxa, Ano-gerssus leiocarpar and Macaranga heudelotii, cyrtosperma senegalense. We can also distinguish the termite mounds in chimneys or epigees (Macrotermes bellicossus, Ma-crotermes subhalinus) which underline the fracturing by quite remarkable alignments. Type B lineaments (geological formations) represent only 11% of validated lineaments. They are found in granitic plutons and meta- morphic rocks that outcrop. Type C lineaments (watercourses and wetlands) represent nearly 37% of the lineaments identified in the study area from the field surveys.

The various field investigations confirm that the lineaments extracted from the satellite images have a structural reality, which reinforces the credibility and validity of the lineaments as a tectonic indicator Directional distribution.

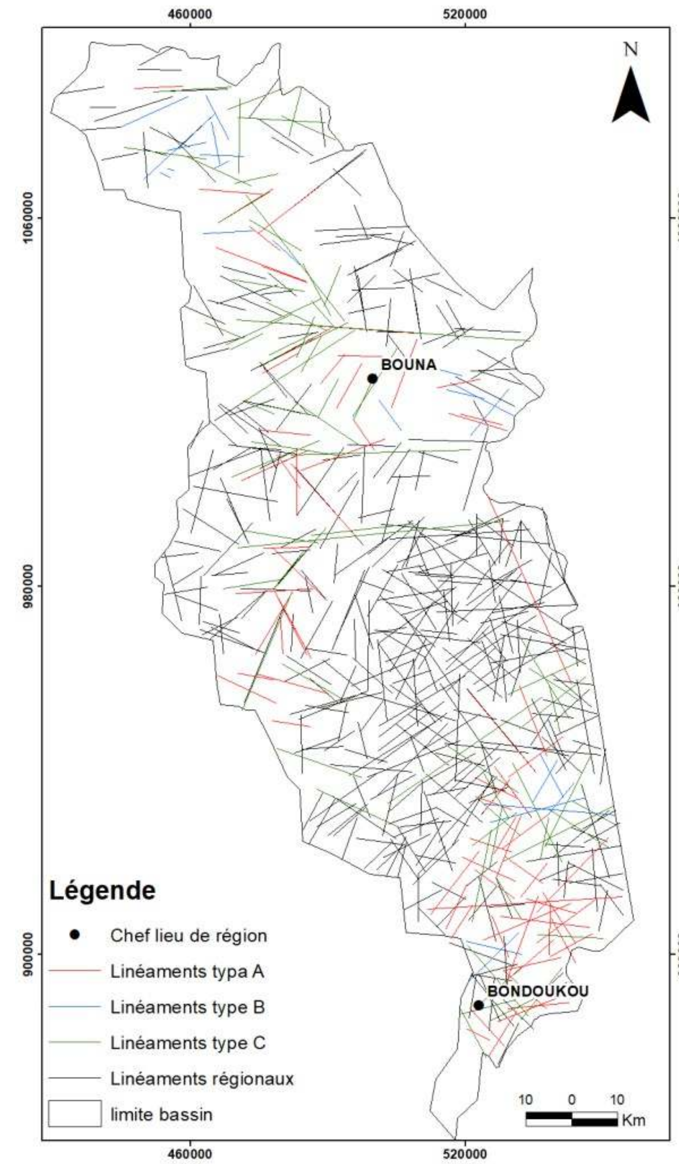
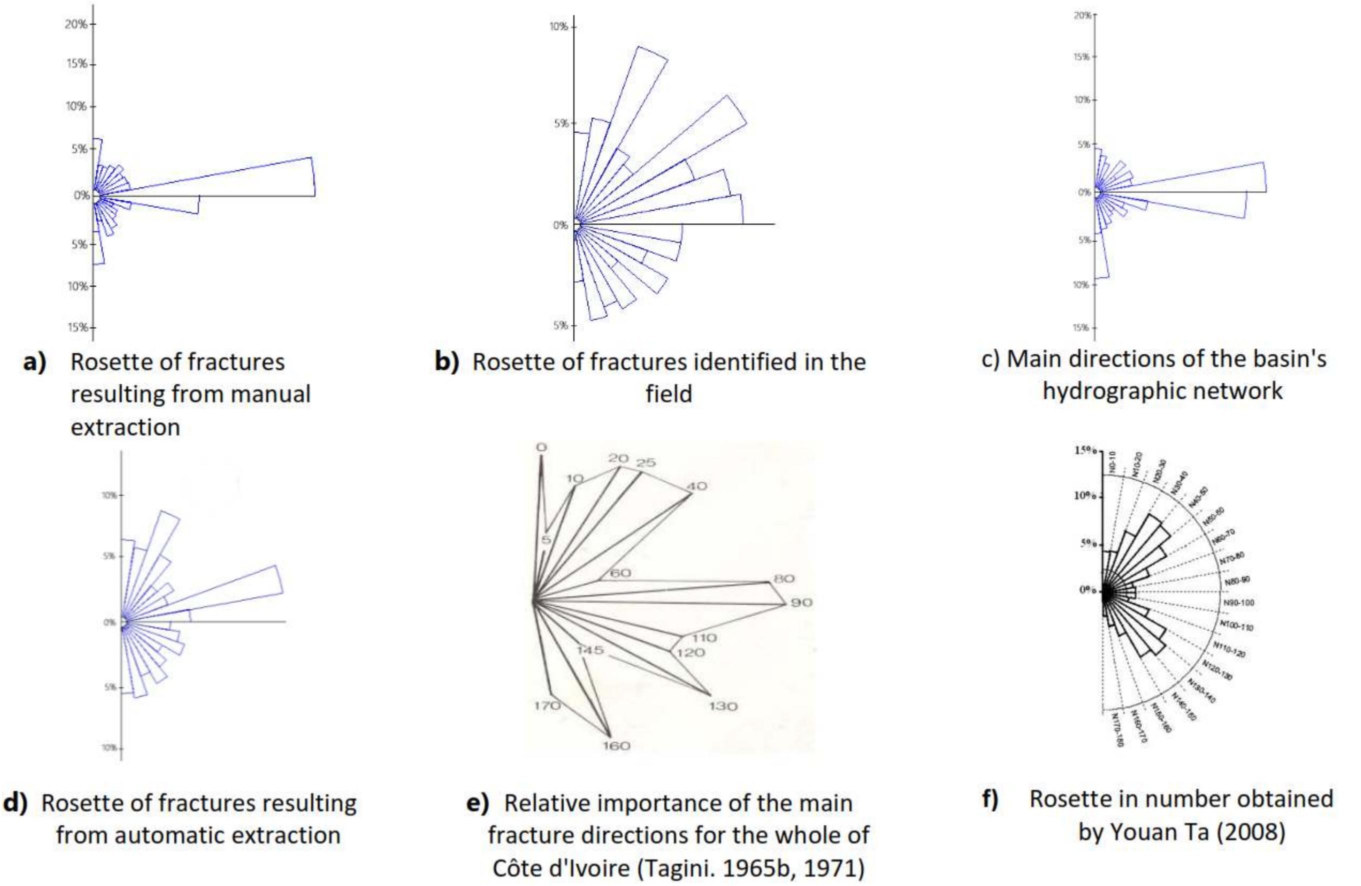


Fig. 5. Map of validated lineaments in the Black Volta basin.

4.2.2 DIRECTIONAL DISTRIBUTION

The directional rosette of lineaments (Figure 6a) shows a homogeneous pattern of orientations throughout. However, three preferential directional families emerge from the ensemble with frequencies that oscillate between 4 and 20%. Thes e are the E- W (N70-80°), N-S (N0-10°; N160-170°) and NE-SW (N40-50°) directions. The comparative statistical analysis of the directional distribution of the lineaments manually extracted from the OLI satellite images showed correlations with several other supports (Figure 6). Indeed, the same directions are found at higher frequencies at the rosette level of the fractures identified in the field (Figure 6b), i.e. 9-10%: N-S (N0-10°; N170-180°) and E-W (N80-90°; N90-100°). These directional families are probably related to the accidents that influenced the layout of the hydrographic network in this area, as shown in Figure 6c, which shows a predominance of the same directional families. The rosette of lineaments from the automatic detection method (Figure 6d) shows at frequencies higher than 6%, the E-W (N70-80°) and NE-SW (N30-40°) directions that are also found on the manual reference map. These results show the main directions of fractures identified throughout the Ivorian territory by Tagini in 1 971 (Figure 6). Locally, the work of [19] in the department of Bondoukou located in the south of the basin, has highlighted the NE - SW and NW-SE directions as the majority directions. Note that the NW-SE directional family is in the minority on the reference map. This would show that they are mainly expressed by the small fractures not considered in this study, i.e. less than 10 m.



a) Rosette of fractures resulting from manual extraction

b) Rosette of fractures identified in the field

c) Main directions of the basin's hydrographic network

d) Rosette of fractures resulting from automatic extraction

e) Relative importance of the main fracture directions for the whole of Côte d'Ivoire (Tagini. 1965b, 1971)

f) Rosette in number obtained by Youan Ta (2008)

Fig. 6. Rosette showing the directional distribution of fractures

4.2.3 POSITIONING OF DRILLINGS

The positioning of visited and unvisited boreholes in the basin (Figure 7) on the global fracturing map validated a number of fractures. It appears from this analysis that they are either superimposed on fractures, on fracture nodes or in the vicinity of fractures in an interval of at least 50 m. This result validates the established fracturing and the structural reality of the lineaments found on the satellite images, thus confirming the effectiveness of the performed specific treatments.

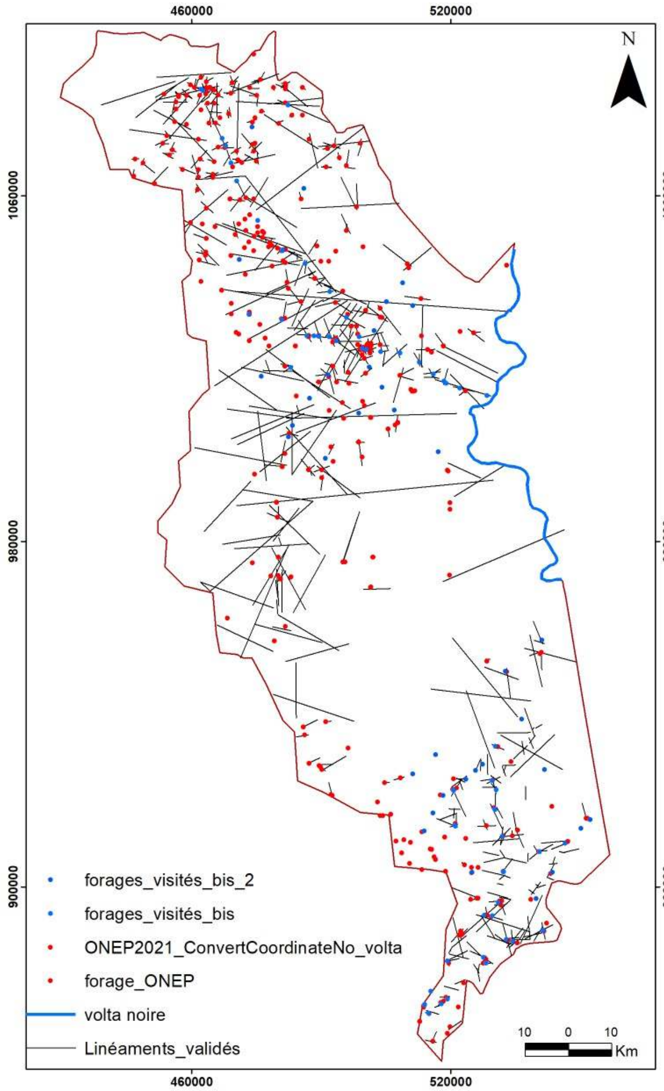


Fig. 7. Validation of the fracturing map by positioning the boreholes in the basin

5 DISCUSSION

5.1 REMOTE SENSING AND STRUCTURAL MAPPING OF MAJOR GEOLOGICAL ACCIDENTS

Knowledge of discontinuous reservoirs is a prerequisite for any hydrogeological investigation in a basement environment. It involves mapping fracture networks by remote sensing and has produced very convincing results in several studies [1], [16], [21], [22], [17], [18], [12].

If it is wise to consider this approach with a certain reserve due to the expertise of the photo -interpreter, it is even more so when the images used are of questionable quality (presence of noise). The Landsat 8 OLI sensor images used in this study have many advantages: The large number of detectors (7000) per spectral band, the design of the sensor and the 12 -bit coding of the data, contribute to the improvement of the information contained in the images compared to previous generations.

The application of the pre-processing and processing techniques implemented resulted in the atmospheric and radiometric enhancement of the images, making them more expressive and more refined for structural mapping. This has facilitated the identification of many structural features. Indeed, the ACPS by merging the images of the different parts of the electromagnetic spectrum, allowed to enhance the differences between the spectral properties of the images thus facilitating the mapping of discontinuities. The calculated indices also increased the contrast between the different geological features in the study area. The mapping of image discontinuities was improved by applying directional filters (Sobel, and gradient of Yésou). These metho ds have been successfully used in the Man region [23], [16], Korhogo [17], Soubré [24] and Tanda [20].

5.2 FIELD TRUTH AND STRUCTURAL VALIDATION

The resulting lineament map was validated from field observations, previous work and the positioning of boreholes drilled in the area.

Validation of the lineaments by "ground-truth" is the most appropriate method because faults of kilometric extension are immediately recognizable [23]. Thus, the matching of major fractures with geological and geomorphological structures identified in the field and the hydrographic network confirms that the lineaments identified are most likely associated with fractures. Indeed, the preferential directions of the identified lineaments present similarities with the directions of the tectonic events that affected the Precambrian basement of Côte d'Ivoire. These are the accidents of the Eburnian orogeny, mainly of N -S direction which influenced the layout of the hydrographic network of the major rivers of Côte d'Ivoire. It corresponds to the direction of the main tributaries of the Volta; the NE-SW birimian direction in reference to the tectonic-metamorphic deformation of the Eburnian cycle at the level of the volcano-sedimentary formations and the E-W direction the most marked, characteristic of the Pan-African orogeny [25].

According to [18], the NW-SE and NE-SW directional families are the most representative in Bondoukou department. In Bondoukou square degree, [26], (2013) shows that the NE-SW (N50-60°, N70-80° and N80-90°) and NW-SE (N140-150°, and N150-160°) directions are the main lineament directions. Here also, this author although using an automatic method confirms the directions N70-80°; N80-90° (E-W); and N140-150°; N150-160° (NW-SE). In this study, i.e. in the entire Black Volta basin, the NW-SE directional class (N120-150°) occurs at relatively low frequencies on the lineament rosette. This is because this directional class would be represented in the basin by the small fractures that are most numerous. At this level, [12] showed that 90.16% of the lineaments mapped in the Black Volta Basin have lengths less than 7km. Thus, there is a strong predominance of small fractures in the basin. In addition, the size of the area considered for this study would explain this trend. Furthermore, [20] indicates that the predominant lineaments over the entire departments of Tanda, Koun-Fao and Transua (localities bordering the basin) are mainly N90-100° (E-W) and N0-10° (N-S) and secondarily N70-80 (NE-SW) and N100-110 (NW-SE). These directions corroborate with the work done by [27] in the Baya basin (Comoé sub-basin). The E-W and N-S directions are precisely the most important in length in the study area.

From all the above, we can affirm that the lineaments extracted manually from the OLI satellite images allow us to characterize the state of fracturing of the Precambrian basement of the Black Volta Basin in Côte d'Ivoire. Otherwise, all these validatio n tests confirm the validity of the detailed lineament map of the Black Volta Basin in Côte d'Ivoire. Consequently, these lineaments can be assimilated to fractures and constitute a very important support for the research of groundwater in the region.

6 CONCLUSION

The present work was articulated around two main activities: the processing of satellite images that led to the extraction of structural lineaments and the validation of lineaments in the field. This study was very important because it allowed to map for once the detailed fracture network of the Precambrian basement of the Black Volta Basin in Côte d'Ivoire. Th ese results were validated by several geological, hydrogeological and geomorphological field studies that demonstrated the structural nature of the lineaments identified.

Indeed, digital processing techniques (ACPS, band ratios) and image filtering (Sobel, Gaussian 3X3 and filter of Yésou et al.) of satellite images have identified 12 09 lineament fractures of length ranging from 7 to 64.2 km. The N -S (N00-10°, N170-180°), E- W (N70-90°); and NE-SW (N30-60°) directions represent the dominant orientations in the area.

The various methods used to identify the network of fractures likely to form fractured reservoirs have proven useful for this purpose. They have made it possible to gather information that was previously unavailable in the region and to contribute to a better understanding of fractured reservoirs for future prospecting in the Black Volta Basin in Côte d'Ivoire. Clearly, the results obtained at the end of this study show that we currently have enough very interesting data that could lead to the discrimination and characterization of the geometry of fractured reservoirs in the future.

ACKNOWLEDGMENTS

The authors would like to thank the Swiss Centre for Scientific Research for the funding of project N°234/2020 between the Programme d'Appui Stratégique à la Recherche (PASRES) and the Laboratoire Sciences du Sol, de l'Eau et des Géomatériaux (SSEG) of the UFR des Sciences de la Terre et des Ressources Minières (STRM), Abidjan, Côte d'Ivoire

REFERENCES

[1] Biémi J., 1992, «Contribution à l'étude géologique, hydrogéologique et par télédétection des bassins versants sub-sahéliens du socle précambrien d'Afrique de l'Ouest Hydrostructurale, hydrodynamique, hydrochimie et isotopie des aquifères discontinus de sillons et aires granitiques de la Haute Marahoué (Côte d'Ivoire),» Thèse de Doctorat. Ès Sc. Nat., Université Abidjan. 1992.

[2] Savané, 1997, «Contribution to the geological and hydrogeological study of discontinuous aquifers of the crystalline basement of Odienné (North-West of Côte d'Ivoire). Contribution of remote sensing and a spatially referenced geographic information system. »PhD thesis in Natural Sciences. University of Cocody (Ivory Coast). 1997; 332.

[3] Sander P., 2006, «Lineaments in groundwater exploration: a review of applications and limitations». Hydrogeology Journal 15 (1), p.71-74.

[4] Mabee, S.B., Hardcastle, K.C., and Wise, D.U. (1994) A Method of Collecting and Analyzing Lineaments for Regional -Scale Fractured-Bedrock Aquifer Studies. Groudwater, vol. 16, n°13, p. 884-894.

[5] Galanos, D. Rokos, «A statistical approach in investigating the hydrogeological significance of remotely sensed lineaments i n the crystalline mountainous terrain of the island of Naxos, Greece», Hydrogeology journal, vol.14, pp.1569 -1581, 2006.

[6] Vanié, L.T.A., Khattach, D., Houari, M.R., Chourak, M., Corchete, V., 2006. Apport des filtrages des anomalies gravimétriques dans la détermination des accidents tectoniques majeurs de l'Anti-Atlas (Maroc). Actes du 3ème Colloque Maghrébin de Géophysique Appliquée, Oujda, 23-30.

[7] El Gout, R., Khattach, D., Houari, M.R., Kaufmann, O., Aqil, H., 2010. Main structural lineaments of orth eastern Morocco derived from gravity and aeromagnetic data. Journal of African Earth Science, (58), 255–271.

[8] Marechal J.C., Wyns R., Lachassagne P., Subrahmanyam K., &Touchard F. (2003). Anisotropie verticale de la perméabilité de l'horizon fissuré des aquifères de socle: concordance avec la structure géologique des profils d'altération. Comptes Rendus Géoscience, 335, p. 451-460.

[9] Lachassagne P., Wyns R. (2005). Aquifères de socle : nouveaux concepts - Application à la prospection et la gestion de la ressource en eau. Géosciences 2, p. 32-37.

[10] Ousmane. B. (1988). Etude géochimique et isotopique des aquifères du socle de la bande sahélienne du Niger (Liptako, Sud - Maradi et Zinder-Est). Thèse Univ. Niamey. 175 p.

[11] Yésou H., Besnus Y., Rolet J. et Pion J. C. (1993).Comparaison et évaluation des données SPOT ERS -1 Seasat Landsat et des données combinées lors d'études de géologie structurale. In 8e congr. Ass. Québéc Télédétection 16ème Symp. Sherbrooke (Canada) pp. 521-526.

[12] Armel. K. Kouame, Marc Youan Ta, O. Zéphir De Lasme, Derving Baka, Carine. A. M. Njeugeut, Fernand K. Kouame, Analysis of Fracture Networks of the Black Volta Catchment in Côte D'ivoire, 2019; Journal of Geography, Environment and Earth Science International (JGEESI) ISSN: 2454-7352, n°46635, Feb. 2019, 1-14p.

[13] Adon G. C., Kouame K. F., Sorokoby V.M., Brouyère S., Affian K. (2014). Extraction automatique des linéaments à l'aide d es images satellitaires Landsat-7 ETM+ en zone de socle précambrien (Haute Marahoué, Côte d' Ivoire). Revue Scientifique Internationale de Géomatique, vol 1, n°1, pp.30-39.

[14] Abdullah A., Akhir M. J., Ibrahim Abdullah I., (2007). A Comparison of Landsat TM and SPOT Data for Lineament Mapping in Hulu Lepar Area, Pahang, Malaysia- European Journal of Scientific Research. Vol 34 N° 3, pp.406-415.

[15] MOORE G. K. ET WALTZ F. A. (1983). Objective procedure for lineament enhancement and extraction. Photogrammetric Engineer. and Remote Sensing, 49, n°5, p. 641-647.

[16] KARNIELI A., MEISELS A., FISHER L., ARKIN Y. (1996). Automatic extraction and evaluation of geological linear features from digital remote sensing data using Hough transform. Photogrammetric Engineering and Remote Sensing, Vol. 62, n° 5, p. 525 -531.

[17] LASM T. (2000). Hydrogéologie des réservoirs fracturés de socle: Analyses statistiques et géostatistique de la fracturation et des propriétés hydrauliques. Application à la région des montagnes de Côte d'Ivoire (Domaine Archéen). Thèse unique de doctorat Université de Poitier, 272p.

[18] Jourda J. P. (2005). Méthodologie d'application des techniques de Télédétection et des systèmes d'information géographique à l'étude des aquifères fissurés d'Afrique de l'Ouest. Concept de l'hydrotechnique spatiale: cas des zones test s de la Côte d'Ivoire. Thèse de Doctorat d'Etat, Université de Cocody, 430 p.

[19] Youan TA M. (2008). Contribution de la télédétection et des systèmes d'informations géographiques à la prospection hydrogéologique du socle précambrien d'Afrique de l'Ouest: Cas de la région de Bondoukou Nord Est de la Côte d'Ivoire. Thèse de doctorat, Université de Cocody-Abidjan (Côte d'Ivoire), 236p.

[20] Abdou B. S.M. (2012). Evaluation des ressources en eau souterraine dans le bassin de Dargol (Liptako-Niger). Thèse de doctorat, Université de Liège, 265 p.

[21] Coulibaly A. (2014). Contribution de la méthode de résistivité électrique (Traînés et Sondages électriques) à la localisation d'aquifères en zone de socle cristallin et cristallophyllien: cas de la région de Tanda, (Nord -est de la Côte d'Ivoire) Thèse de doctorat. Université de Cocody-Abidjan (Côte d'Ivoire). 211p.

[22] Akokponhoue H. B., Yalo N., Lasm T., Youan TA M., Alassane A., Kouamé K. J., Akokponhoue Y. N., Hounton C.C., Suanon F. (2017). Contribution of Remote Sensing to the Structural Mapping of Aquifers with Large Water Flows in the Crystalline Hard- Rock in the Department of Donga (North-West of Benin).Int. J. of Emerging Tech. and Adv. Eng., Vol. 7, p.392-403.

[23] Lasm T. ET Razack M. (2001) Lois d'échelle dans la fracturation des roches dures cristallines et dans le reseau hydrographique associé. Compte Rendu Académie des Sciences Paris, Science de la Terre et des planètes, n° 333, p. 225-232.

[24] Darcel C. (2002). Corrélation dans les réseaux de fractures: caractérisation et conséquences sur les propriétés hydrauliques. Thèse de doctorat. Université Rennes 1, France. 223p.

[25] Kouame K. F. (1999). Hydrogéologie des aquifères discontinus de la région semi-montagneuse de Man-Danané (Ouest de la Côte d'Ivoire). Apport des données des images satellitales et des méthodes statistique et fractale à l'élaboration, d'un système d'information hydrogéologique à référence spatiale. Thèse 3ème cycle, Univ. Cocody-Abidjan, (Côte d'Ivoire), 194 p.

[26] YAO K.T. (2009). Hydrodynamisme dans les aquifères de socle cristallin et cristallophyllien du sud-ouest de la Côte d'Ivoire: cas du Département de Soubré. Apports de la télédétection, de la Géomorphologie et de l'hydrogéochimie. Thèse de doctorat, Université de Cocody, 284 p.

[27] Faillat J.P. (1986). Aquifères fissurés en zone tropicale humide: structure, hydrodynamique et hydrochimie (Afrique de l'Ouest). Thèse Univ. Languedoc (Montpellier), 534p.

[28] Jofack-Sokeng V-C., Kouame K. F., Youan Ta M., Saley M. B., Kouame K. (2014). Extraction automatique des linéaments sur les images satellitaires par réseaux de neurones: contribution à la cartographie structurale du socle précambrien de la régi on de Bondoukou (nord-est de la Côte d'Ivoire), Revue Scientifique Internationale de Géomatique, vol. 1, n° 1, pp. 4-17.

[29] Mangoua J. (2013). Evaluation des potentialités et de la vulnérabilité des ressources en eau souterraine des aquifers fissurés du bassin versant de la Baya (Est de la Côte d'Ivoire). Thèse de doctorat unique, Université Nangui Abrogoua, 171p.